SOUND RADIATED BY SPHERES FALLING IN POLY(ETHYLENE OXIDE) SOLUTIONS

by

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UNITED STATES
NAVAL POSTGRADUATE SCHOOL

THESIS

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ABSTRACT

Sound radiated by spheres freely falling in aqueous solutions of poly(ethylene oxide) WSR-301 at concentrations 0 and 100 wppm was investigated. In solution of 0 wppm concentration, only those spheres with calculated Reynolds numbers (based on the terminal speed) at or above the critical value radiated sufficient energy to be detected above the background. This sound consisted of frequent, distinct noise bursts. In the 100 wppm solution, all spheres with Reynolds numbers near the critical value displayed an increase in speed and a reduction of radiant sound to below background. The one sphere definitely in the supercritical region did not significantly change in speed, and the radiant sound was not reduced as much as for the other spheres. These observations are consistent with the assumption that the noise bursts are produced in the wake associated with laminar separation, and with the previous observation that polymer addition shifts the critical Reynolds number to higher values.

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1. Introduction

The reduced drag exhibited by dilute polymer solutions was first recognized by Toms [1]. He reported drag reductions of 50 percent with 0.01 percent solutions of polymethylmethacrylate in pipe flow. Subsequent studies [2], [3], [4], [5], [6] with different polymers for turbulent flow through pipes ranging from 0.1 to 5 cm ID substantiated Toms' findings.

Thurston and Jones [7] by applying a soluable polymer coating to a streamlined body of torpedo shape, obtained drag reductions of 18 percent. Baronet and Hoppman [8] injected polymer solutions in flow about cylindrical bodies with spherical ends, and demonstrated that significant drag reductions are obtained in very dilute solutions. Crawford and Pruitt [9] obtained drag reductions of 80 percent on a model torpedo in a solution of 100 wppm concentration. Merril, Smith, and Chung [10] using a torpedo model, observed a drag enhancement for concentrations greater than 40 wppm. Baronet and Hoppman made a similar observation.

There have also been investigations into the effect of polymer solutions in reducing the drag of spheres. Ruszczycky [11] using spheres with diameters from 0.375 inch to one inch, in concentrations of 2500-15000 wppm of polyox WSR-301, reported a maximum drag reduction of 26 percent at a concentration of 7500 wppm. Hayes [12] also investigated the drag reduction of spheres. His area of interest covered diameters from 0.038 inch to one inch and Reynolds numbers from 10^3 to 6×10^4. Hayes reported a maximum drag reduction of 54 percent at a concentration of 100 wppm.

Lang and Patrick [13] used spheres with diameters up to 2.5 inch in their investigation of drag reduction. For Reynolds numbers up to 2 x 10^5, Lang and Patrick reported a maximum of 69 percent drag reduction for a concentration of 1000 wppm. Dye streak photographs demonstrated that for Reynolds numbers less than 2 x 10^5 the polymer solution shifted the separation point rearward. This delay of the separation point reduced the size of the sphere wake. The turbulent mixing in the wake was less intense than in water.

Chenard [14] demonstrated the drag reduction for spheres in the Reynolds number region 4 x 10^4 to 3.5 x 10^5 and showed that polymer addition shifted the critical Reynolds number to higher values.

As a rigid body moves through water, hydrodynamic noise is generated, which has its origin in the turbulent boundary layer and the vortices found in the wake. Since it is well known that polymer solutions reduce the drag of a body, it is logical to ask what effect, if any, does a polymer have on radiant hydrodynamic noise of a moving body.

A study of the effect of drag reducing polymers on the radiant noise due to hydrodynamic turbulence would provide another avenue of approach in the study of the drag reduction phenomenon. The acoustical approach would be especially powerful when combined with conventional hydrodynamic observations, e.g., correlation of radiant noise with dye streak photography. Any reduction in radiant noise by polymer solutions would have practical application in hydrodynamic noise reduction of underwater vehicles, the reduction of the "humming effects" of submerged hydrophone cables, etc.

The purpose of this project is to investigate the radiant noise from a sphere freely falling in various concentrations of poly(ethylene oxide) solution. A blunt body was chosen because most of the radiated noise from such a body should come from the wake and only a negligible amount from the boundary layer, thereby isolating the former effect for study. In particular, spheres were chosen because of the large amount of information available about spheres in polymer solutions and ordinary fluids.

2. History of Radiated Noise Investigations

The first scientific investigation of hydrodynamically radiated sound is generally attributed to Strouhal [15] in his study of aeolian tones generated by circular cylinders. He showed that the frequency of the sound and the frequency of the vortex shedding were the same. This frequency he expressed in the relation $f = .185\ U/d$, U being the flow velocity and d the cylinder diameter. There have been subsequent investigations in this area. Several of these will be discussed.

Stowell and Deming [16] rotated cylindrical rods in air about their midpoint, and investigated the sound emitted due to the shedding vortices. They showed that the sound power was proportional to the 5 1/2 power of the rotational speed, and they substantiated the Strouhal formula for the frequency.

Gerrard [17], studying flow past circular cylinders in air, showed that the sound produced by the vortex street possessed a dipole pattern which consisted of a fundamental frequency accompanied by harmonics. His experimental results demonstrated that the radiated intensity was proportional to the fourth power of the flow velocity. At Reynolds numbers greater than 10^5, the periodic characteristics of the flow were replaced by random fluctuations of turbulence.

Etkin, Korbacher, and Keefe [18] presented the following summary of acoustic radiation from a stationary cylinder:

a. Acoustical output power varies as U^n, where n is 5 to 6 dependent upon dimensions of the cylinder and the Mach number.

b. A tone is produced having the same frequency as the wake, and it has the directionality of a dipole with its axis normal to the stream. The tone is associated with the lift force.

c. Another tone, having twice the frequency of the wake, is associated with the drag force. This tone has the directionality of a dipole with its axis parallel to the stream.

Richardson [19] working with a towed cylinder in water, demonstrated the dipole nature of the sound field.

The two-dimensional acoustical radiation from a cylinder can not be simply extended to the three dimensional case of a sphere. No experimental data could be found for radiated noise produced by flow about a spherical body. Since it is believed that the major source of noise radiated by a blunt body eminates from the wake, it is useful to look at some of the information on the wake structure for the flow past a sphere.

Moller [20] investigated the wake formation for spheres in steady motion through water, with Reynolds numbers of 150 to 10,000. The vortex formation and shedding became apparent at Reynolds number of 450. The shedding vortices seemed to be linked together forming a chain. Discrete vortices began forming at Reynolds number of 1000 and became predominant at Reynolds number of 1500.

Winny [21], working with air flow about spheres, reported intertwining helical vortices in the range of Reynolds numbers from 2000 to 8000. He used a crude condenser microphone connected to an aperture on the surface of the sphere and observed that near the critical value of the Reynolds number (about 1.3×10^5) he heard a "crackling sound with a higher note forming the basis of the noise". The noise was the loudest when the aperture was positioned near the point of separation. Oscillographic records show that this noise consists of short bursts of sound occurring at random times.

Ermish [22] reported that two vortex lines began forming interlacing spirals commencing at about a Reynolds number of 8400.

Foch and Chartier [23] showed for Reynolds numbers slightly less than 1.25×10^5, the wake consisted of two intertwining vortex filaments, whose points of origin on the sphere moved about the sphere. At a Reynolds number of 1.3×10^5, the portion of the wake immediately behind the sphere was conical in shape with the apex downstream. Within this region the water moved in a coil motion perpendicular to the wake axis of symmetry. At a Reynolds number of about 2.7×10^5, the wake seemed to spiral, but the "coiling water" was retained.

The only experimental results concerning the ffect of poly-(ethylene oxide) on radiated noise were those of Killen and Crist [24]. They studied the effects of Polyox WSR-301 on the radiated noise produced by the turbulent boundary layer of a circular cylinder revolving about its axis. A reverberant tank was used to investigate the radiant noise at concentrations of 0, 10, 100, and 1000 wppm. Sound power reductions of 20 dB were observed in the frequency range 20 KHz to 100 KHz for 1000 wppm concentration. Little influence could be found in the frequency range 1 KHz to 20 KHz.

3. Experimental Apparatus

3.1 General. The ideal way to conduct radiated noise measurements would be to run a test vehicle in an immense body of water with a low ambient noise level. Such a body of water is usually not available; but even if it was, the necessity of ejecting polymer from the vehicle would create unwanted noise. For these reasons it is desirable to conduct a laboratory experiment utilizing a tank filled with polymer solution.

3.2 Test Spheres. The spheres were selected to provide Reynolds numbers (based on the terminal speed), from 3×10^4 to 8.6×10^5 with special emphasis in the region near the critical Reynolds number of about 3×10^5. See Fig. 1.

The characteristics of the six different test spheres used are listed in Table I.

The spheres are shown in Fig. 2.

The six-inch aluminum sphere consisted of two hemispheres, within which various weights could be inserted. A heavy lubricant was applied to the mating surfaces of the hemispheres, and to prevent water leakage, GC Electronics # 58-2 vinylite cement was applied on the seam after the hemispheres were joined.

The three-inch aluminum sphere had a one inch by two and one-half inch cylindrical hole, which was sealed by a cap, held in place by a steel bolt. An O ring was used to prevent water leakage. Two cylindrical lead slugs, each weighing 131 gm, could be fitted into the cylindrical hole. Each slug had a longitudinal hole through which passed the cap-securing bolt.

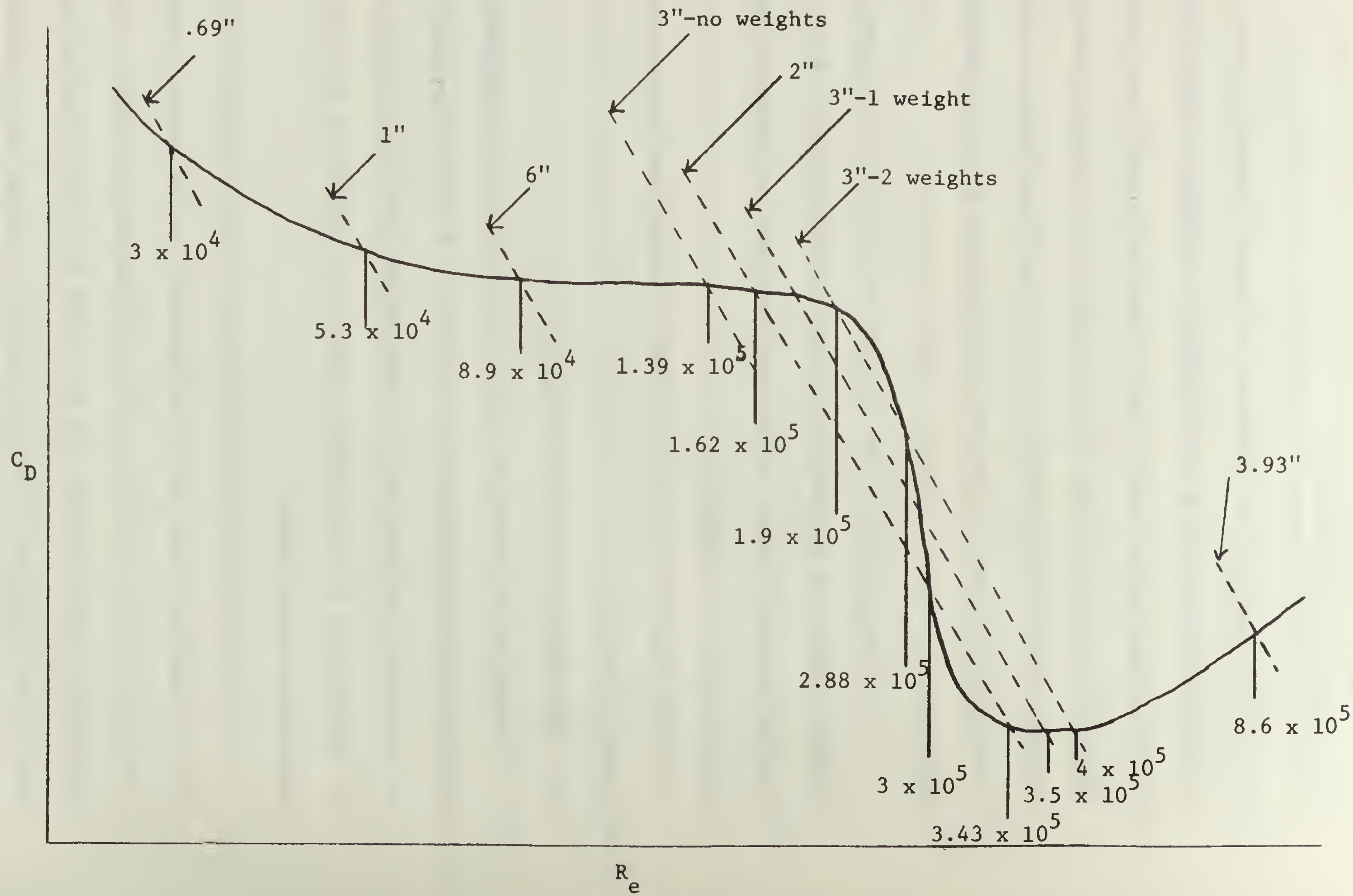


Figure 1. Calculated Reynolds Numbers

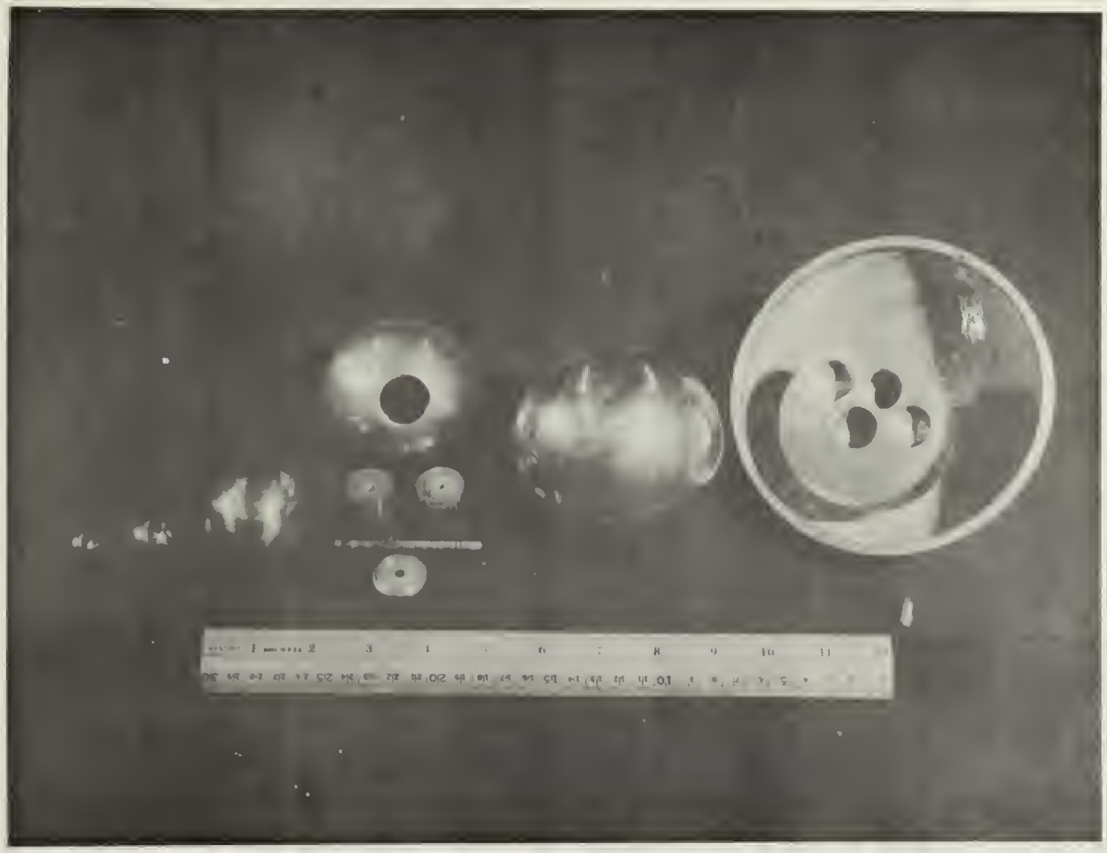


Figure 2. Test Spheres

TABLE I

Test-Sphere Characteristics

Diameter (inch)	Material	Weight (lb)	Buoyancy (lb)	Weight Minus Buoyancy	Reynolds Number
6	Aluminum with an enclosed brass weight	4.42	4.07	0.35	8.9×10^4
3.93	Solid brass with a steel slug	9.51	1.15	8.36	8.6×10^5
3	Aluminum with two enclosed weights	1.88	0.51	1.37	1.9×10^5 2.88×10^5 4×10^5
	one enclosed weight	1.59	0.51	1.08	1.65×10^5 2.99×10^5 3.5×10^5
	No weights enclosed	1.30	0.51	0.8	1.39×10^5
2	Solid steel	1.18	0.15	1.03	1.62×10^5 3×10^5 3.43×10^5
1	Solid steel	0.15	0.02	0.13	5.3×10^4
0.69	Solid steel	0.05	0.01	0.04	3×10^4

The 0.69 inch, one inch, and the two inch spheres were solid steel.

The 3.93 inch sphere was solid brass with a one-half inch diameter hole on a diameter which initially was sealed with tacky wax.

It was found necessary to adapt the aluminum and brass spheres for use with a magnetic releasing device to be discussed later. A steel bolt with a one fourth inch flat head was inserted into the 6 inch sphere. This bolt protruded about one-eight inch from the sphere surface. The steel bolt of the 3 inch sphere was flush with the surface and it provides the necessary magnetic coupling. To adapt the 3.93 inch sphere, it was necessary to drill a larger hole and insert a 1.5 inch diameter iron slug. The ends of the slug conformed to the curvature of the sphere.

All sphere surfaces were prepared by polishing with a 320 and 564 grit emery cloth, and finishing with a 600 alumna polish.

3.3 Drop Tank. The drop tank, Fig. 3, was a metal cylinder measuring six feet deep and three feet in diameter, with three port-holes for visual observation. The tank rested on four three inch by three inch vibration insulation pads which were supported by a three foot by three foot by four inch wooden pallet. A pad of rubberized packing material was used on the bottom of the tank to cushion the impact of the spheres. This pad was pulled up to retrieve the spheres.

3.4 Sphere Releasing Mechanism. At all times the sphere was released with its top about one inch below the water surface.

The following devices were tried as releasing mechanisms:

1. Solonoid action releasing spheres through a six inch line attached to the sphere.

2. Manual operation of a quick release hook, with the sphere attached to the hook by a six inch line.

3. Releasing the sphere by hand when an audible 8 kHz reference signal was turned off.

4. An electromagnet .

The first two methods proved to be unsatisfactory because the releasing process generated too much unwanted noise. The third method was quiet, but it did not provide any indication of when the sphere was actually released.

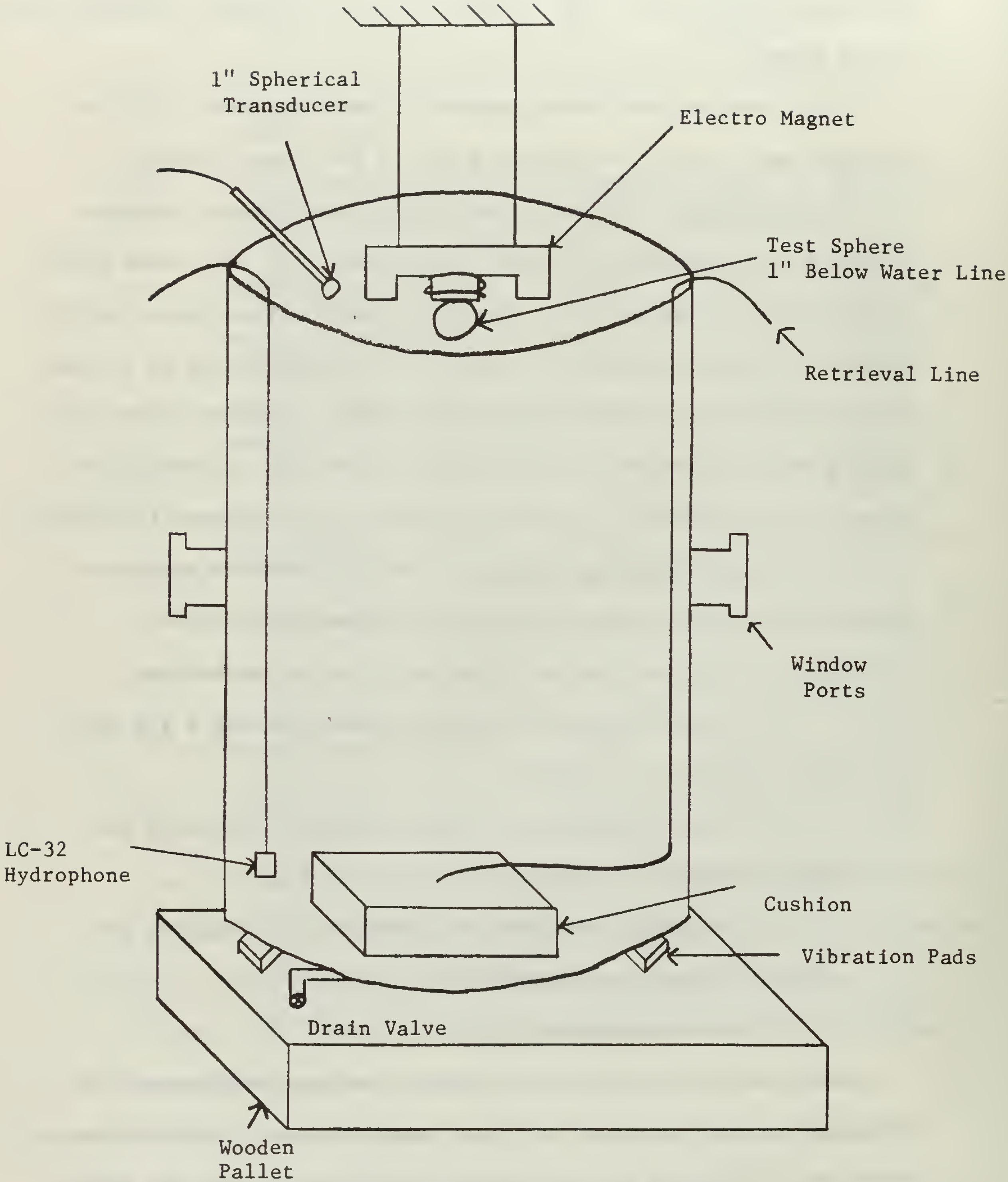


Figure 3. Drop Tank

The electromagnet provided both a quiet release and the necessary time mark. The electromagnet was suspended from the ceiling with the face of the center core about one inch below the water line. The DC power source was adjusted to provide a minimum output necessary to hold the various spheres. This output ranged from 0.2 to 1.8 amperes. Initially all the power to the magnet was turned off to release the sphere, but the back EMF of the coil placed a very undesirable transient on the measurement system. This problem was eliminated by placing a 22 ohm resistor and a 0.01 capacitor in parallel with switch S1 (See Fig. 4). When switch S1 was opened, the current was reduced sufficiently to release the sphere without placing a transient on the recording system.

3.5 Calibration Tone and Release Mark. A General Radio oscillator and a one inch spherical barium titinate transducer were used to establish a 5 kHz reference level in the tank. When switch S1 (Fig. 4) was opened, the current to the electromagnet was reduced releasing the sphere, and the reference level was turned off, thereby providing on the tape the necessary release mark.

3.6 Hydrophone. An Atlantic Research LC-32 hydrophone was used which had a nearly flat response curve up to 60 kHz, Fig. 5. Since it was found that the characteristics of the received noise did not change significantly when the hydrophone was positioned at various levels, all data runs were taken with the LC-32 hydrophone positioned two inches from the side wall and fifty-four inches below the water line.

3.7 Amplifiers. Since the signal was small, low noise amplifiers were selected. A Tektronix type 1121 and a Hewlett-Packard 466A were used, Fig. 6. The Tektronix provided a 40 dB gain and the Hewlett-Packard contributed another 20 dB. The Hewlett-Packard VTVM provided continuous monitoring of the background level and added another 20 dB gain before entering the tape recorder.

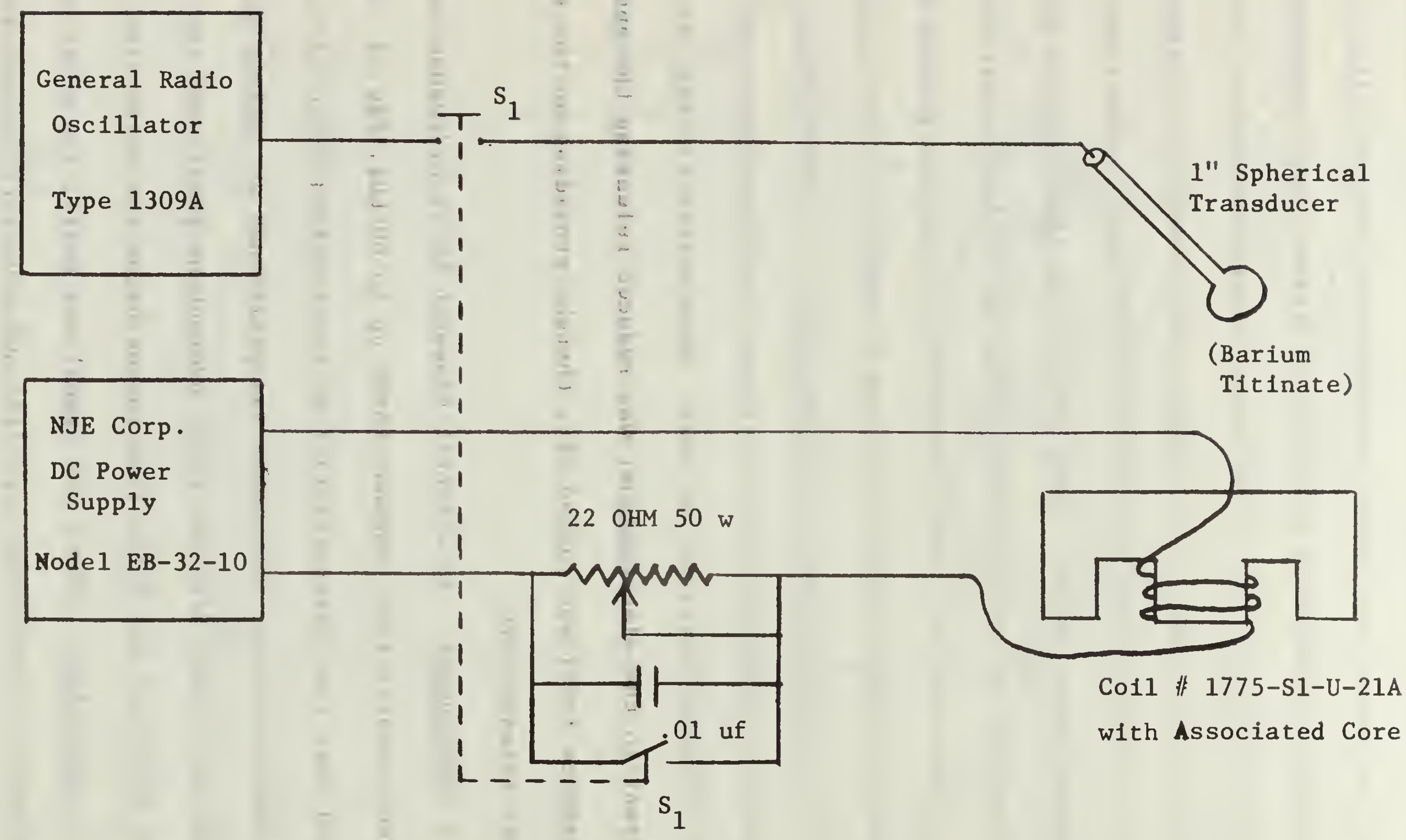


Figure 4. Sphere Releasing Mechanism

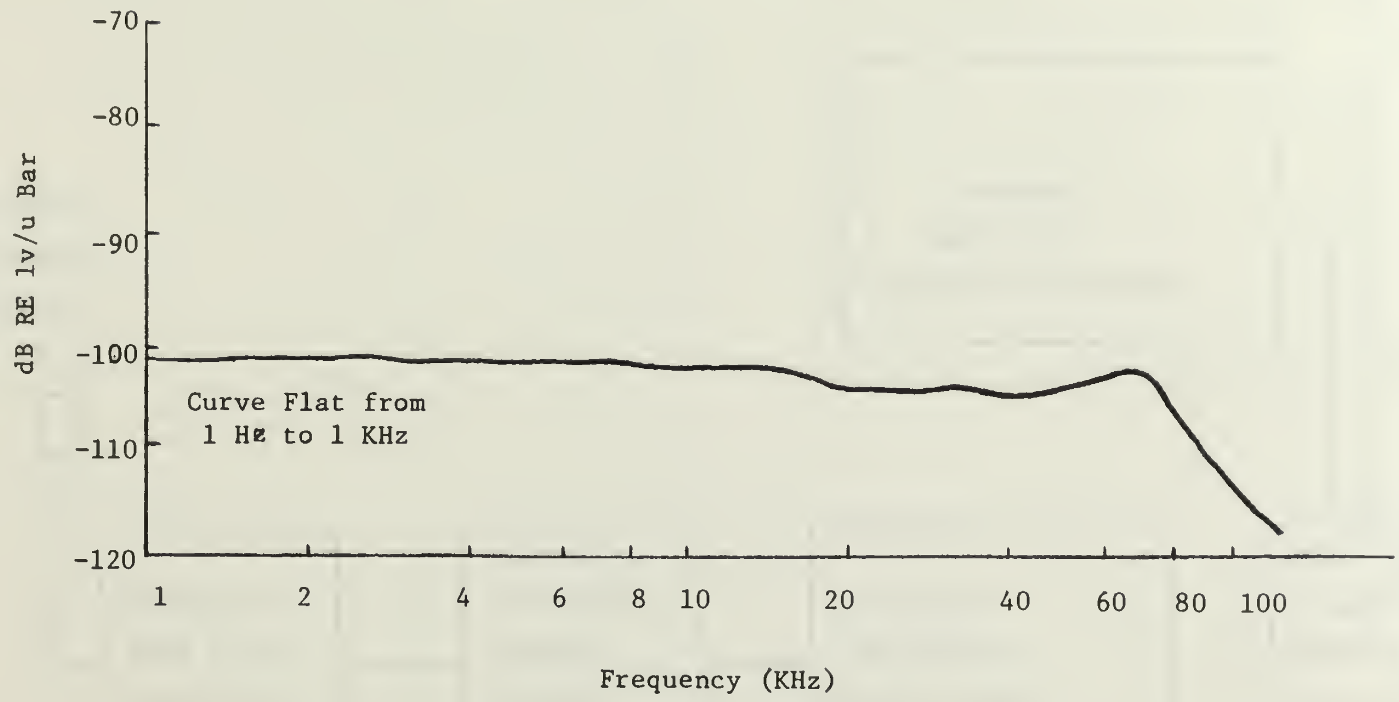


Figure 5. Response Curve of LC-32 Hydrophone

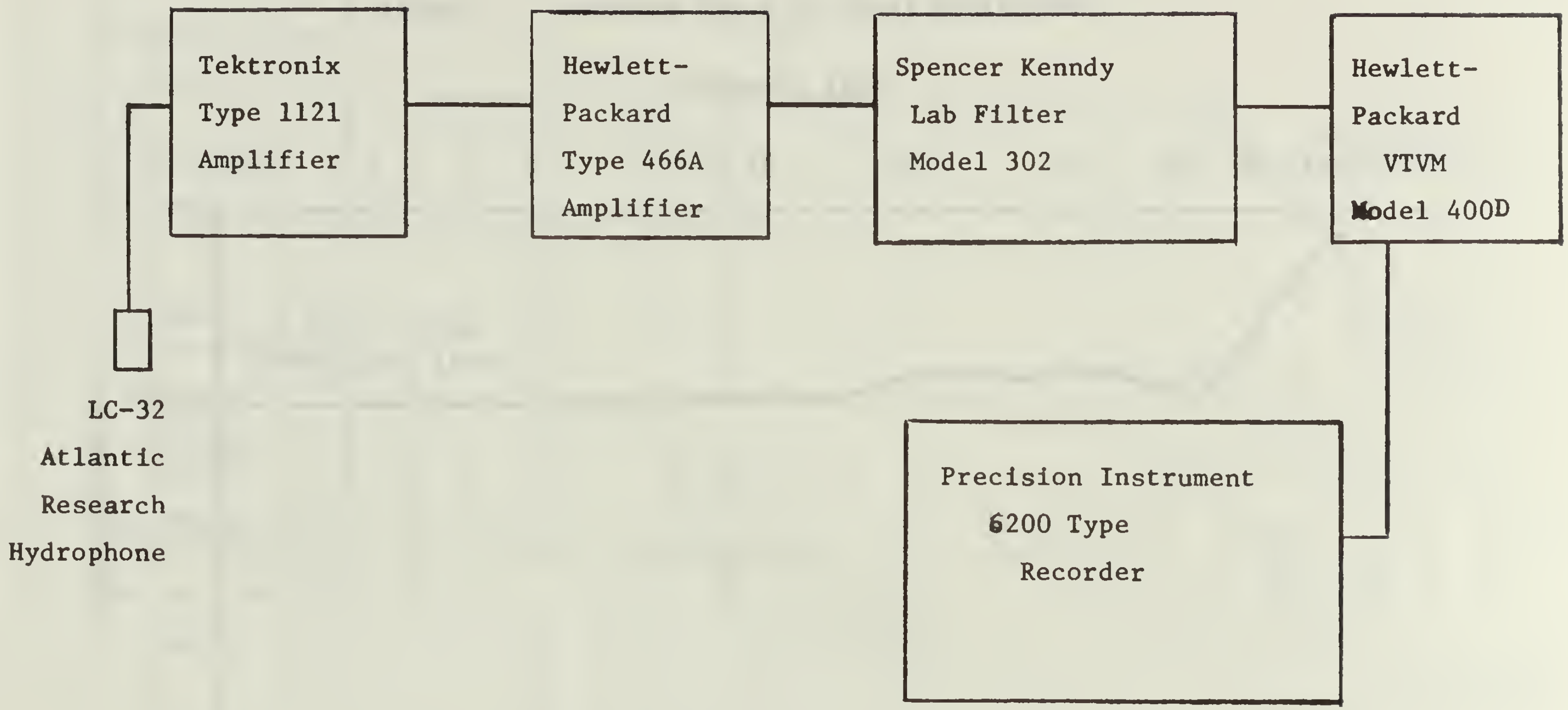


Figure 6. Electronics for Data Collection

3.8 <u>Tape Recorder</u>. All information was recorded on a four channel Precision Instrument 6200 tape recorder. The direct mode of operation was used, recording at 37.5 ips, which provided an essentially flat frequency response from 300 Hz to 100 kHz.

4. Experimental Considerations

4.1 Background Noise. To increase the signal to noise ratio, selective filtering was employed. A Spencer Kennedy Lab variable filter model 302 was set to pass frequencies greater than 2 kHz and less than 100 kHz. These settings, selected by trial-and-error, provided the best signal to noise ratio, while retaining a frequency band of significant interest.

Even with low noise amplifiers and selective filtering, much difficulty was still encountered with periods of high background level (sometimes as much as 10-15 dB above "normal"). This disturbance was unpredictable and appeared to be an electromagnetic disturbance from some undetermined activity in the building. This unpredictable background placed a definite restraint on the times when data could be profitably collected.

At one time the outside of the tank was totally insulated with one inch fiber glass. This treatment reduced the average background level about 1 dB. Since this improvement was minimal, the insulation was removed.

4.2 Reverberant Versus Anechoic Tank. The use of an anechoic tank would simplify the interpretation of the results, as well as allow the determination of absolute sound levels. However, the anechoic tanks would be difficult to clean after use with a polymer and other users of these tanks objected because of possible contamination. Because of this, it was decided to use a reverberant tank.

In order to insure that the reverberant tank did not significantly ffect the results, spheres were dropped in a water filled anechoic tank with a hydrophone placed at various depths and distances from the path of the sphere. The resulting noise signatures were qualitatively indistinguishable from similar drops in the reverberant tank.

4.3 Accelerating Sphere. Ideally, radiant noise data should be recorded with a given sphere moving at terminal speed. The drop tank employed was not deep enough to enable all the spheres to reach terminal speed. Therefore, radiant noise measurements from accelerating spheres had to be considered. This procedure, while complicating the interpretation of the results and limiting the conclusions, was reluctantly adopted because of the expense and time involved in attempting to achieve terminal speed.

5. Polymer

5.1 Type of Polymer Used. The polymer selected was Polyox WSR-301 manufactured by Union Carbide. This grade was selected because of its well demonstrated drag reducing properties.

5.2 Mixing Technique. If the granular Polyox WSR-301 were placed in the water, large globules would form and the Polyox would not go into solution. To facilitate the mixing procedure, the granular Polyox was first suspended in a nonsolvent, Polgglycol P-400. To make a concentration of 100 wppm, 112 gm of Polyox was added to 1000 cm^3 of polyglycol.

The mixing technique first tried consisted of adding the polyox-polyglycol suspension to the water by pouring it in the stream of water from a filling hose at the top of the tank. After the tank was filled, this solution was mixed with a rotary mixer for about two hours. This mixing technique proved to be unsatisfactory as evidenced by the accumulation of polymer discovered at the bottom of the tank when it was cleaned.

A more homogeneous solution was obtained by simultaneously filling the tank through the drain valve on the bottom and from a hose at the top while adding the polyox-polyglycol suspension. Then the rotary mixer was used for one hour.

6. Experiments

6.1 Data Collection. The procedure followed for each session of data collection was as follows: After the solution had been prepared, the fluid temperature and the distance below the water line from which the sphere would be released were recorded. The background level was checked to insure that an acceptably low level (-115 to -118 dB) was present prior to commencing a run. The tape recorder was started, and the tape was annotated with the date and run number. The background noise was recorded for several seconds and then the 5 kHz test signal was turned on for several seconds. The level of this test signal was always set at -100 dB as indicated by the VTVM. Then, the releasing switch was opened, dropping the sphere and turning off the test signal to mark the exact time of the release. The tape then recorded the radiant sound of the falling sphere and the crash of the sphere striking the bottom. The tape recorder was then turned off. The sphere was retrieved and positioned for the next run. An interval of about five minutes between runs was allowed to insure that all motion in the tank would damp out. The entire procedure was repeated until all spheres had been dropped five or more times in the solution under investigation.

6.2 Description of Radiant Sound. Since the time to fall the fixed distance was on the order of a few seconds, all runs were played back at one-tenth speed to stretch the run time to ten seconds or more. The speaker provided an invaluable aid in qualitative analysis. With the speed reduction, the various parts of the run could easily be distinguished. When the test signal stopped the sphere began to fall, quietly at first but, after the sphere had attained sufficient speed, the sound characteristic of the sphere was heard. The major contributions to this radiant sound consisted of noise bursts which sound (at the reduced speed) like "blurp". These noise bursts will be referred to hereafter as "blurps". The frequency of occurrence of these blurps seemed to increase as the speed of the sphere increased. The run ended with the characteristic swishing sound of the sphere penetrating into the shock absorbing layer of packing material.

6.3 Quantitative Measurement Techniques. A survey of various techniques for quantitative analysis was conducted. The following measurement techniques were tried with varying degrees of success. Refer to Fig. 7.

1. A General Radio 1558A Octave Band Analyzer was used to obtain band levels versus time. The bands measured (in kHz) were 1.5-3, 3-6, 6-12, 12-24, 24-48, 48-96, and all pass. These band levels were recorded on a Bruel and Kjaer type 2304 recorder. A typical plot is shown in Fig. 8a.

2. A General Radio 1900-A Wave Analyzer was used to obtain band levels in one kHz steps from 3 kHz to 32 kHz. The bandwidth used was 500 Hz. The DC output of the wave analyzer proportional to the input was recorded on a Varian F-100 magnitude-time Plotter. A typical plot is shown in Fig. 8b. This analysis technique was not extensively employed because of the great number of plots needed to completely analyze each run.

3. A Hewlett-Packard 3400A RMS Voltmeter provided a DC voltage proportional to the RMS value of the recorded sound signal. The DC value was integrated by an Electronic Associates, Inc. TR-20 Analog Computer. The Varian F-100 magnitude-time plotter was used to obtain a plot of this integrated value. A typical plot is shown in Fig. 8c.

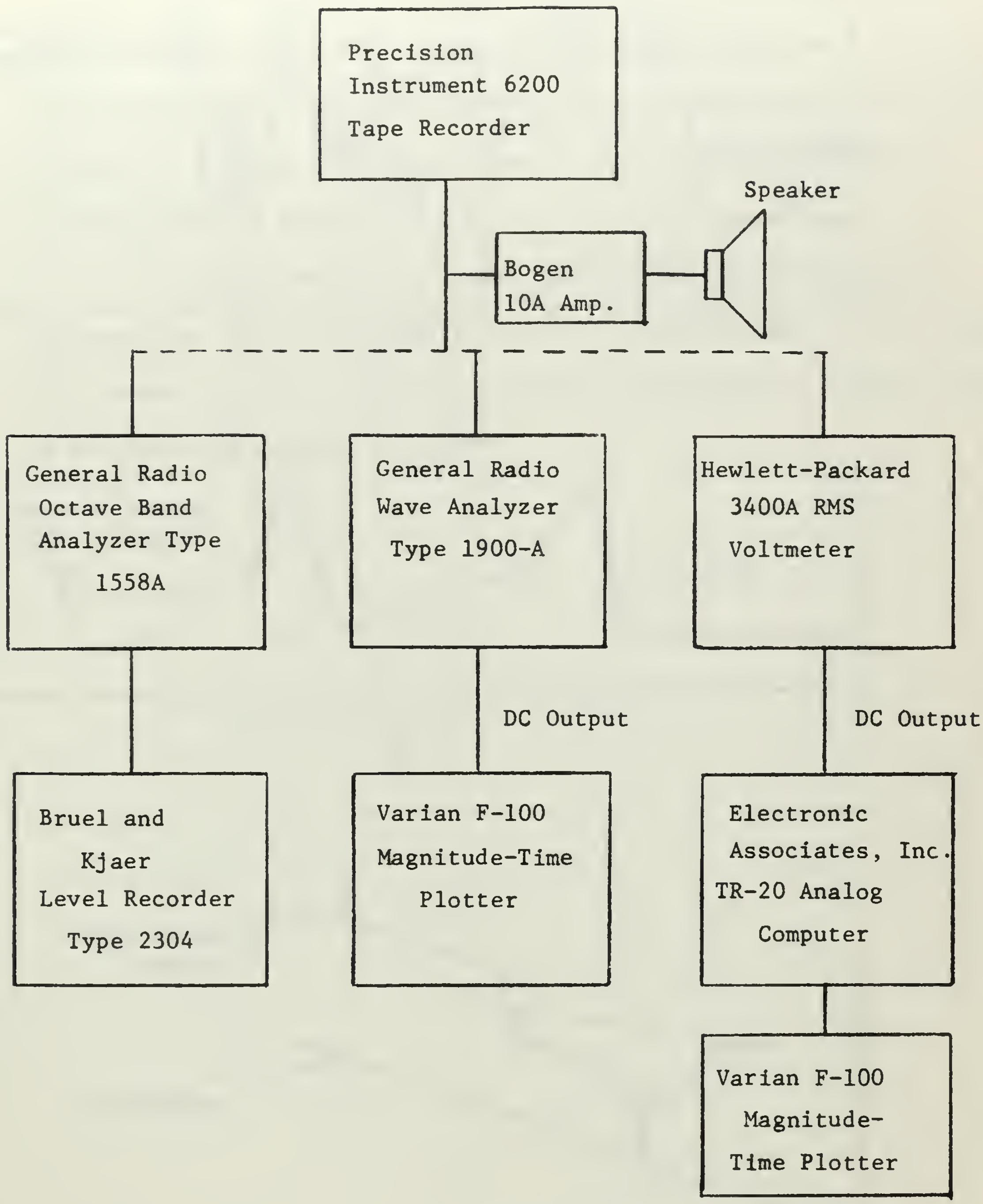


Figure 7. Electronics for Data Analysis

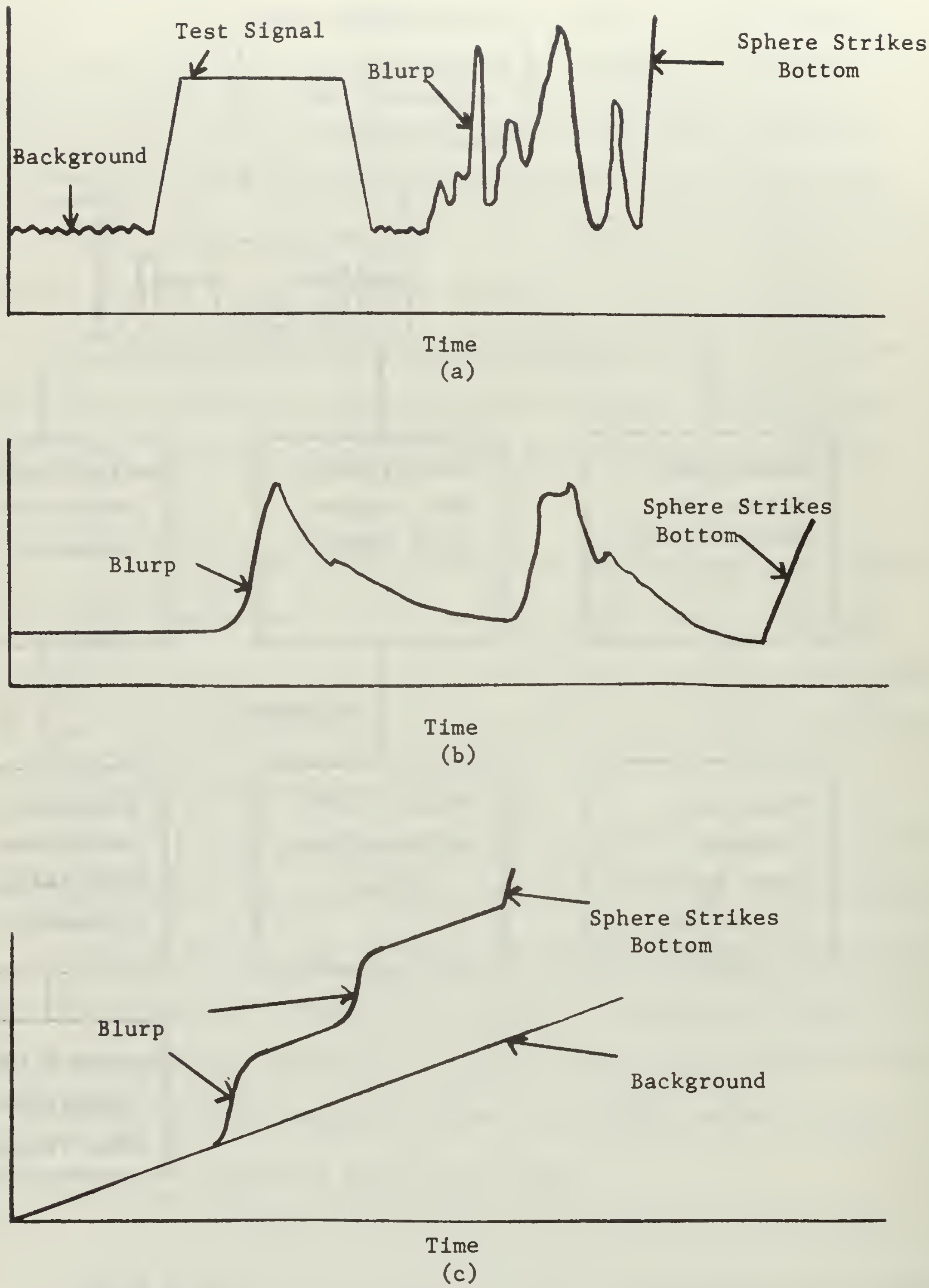


Figure 8. Typical Recording Plots

4. A Kay Electric Co. 675 B Missile Data Reduction Spectrograph (Missilizer) provided spectrograms of intensity as a function of frequency and time. This device also provided plots of magnitude (linear in voltage covering a range of 10 to 1) as a function of frequency (60 Hz bandwidth).

A significant broad range (150-15,000 Hz) could only be obtained for those runs with a run time (in real time) of less than 0.8 seconds. It was therefore frequently necessary to analyze only a portion of the total run time.

7. Results

All times and frequencies referred to are for real times and frequencies. The 0 and 100 wppm concentrations were most extensively studied, and these data will be presented except where indicated otherwise.

The experimentally determined times for a given sphere to fall the fixed distance are listed below:

Time (sec. $\pm$ .01 sec)

Sphere	0 wppm	12.5 wppm	100 wppm
3.93 inch	.68	.68	.65
3 inch - 2 wts	.92	.88	.78
3 inch - 1 wt	1.06	.94	.82
3 inch - no wt	1.18	1.04	.91
6 inch	2.88	2.38	2.37
2 inch	.8	.77	.69
1 inch	.97	.92	.75

All spheres except the 3.93 " sphere took significantly less time to reach the bottom in the 100 wppm concentration as compared with the 0 wppm concentration. The Reynolds number of the 3.93 " sphere is in the supercritical region where Chenard's data indicates that the drag reduction is small.

1. Missile Data Reduction Spectrograph. For the 3.93 inch sphere in 0 wppm concentration (Fig. 9) blurps appeared suddenly at distinctive points in time. Within the frequency limitation of the spectrograph (150-15,000 Hz) and the experimental limitation to frequencies greater than 2 kHz, most of the blurps displayed a

continuous band of frequencies. A few of the blurps showed frequencies for only a portion of the range. For all frequencies, the onset of the blurp occurred at the same time, resulting in a distinct leading edge of the blurp on the spectrogram. The frequency components with the greatest strength seemed to be within a band of 3-11 kHz. The frequency spectrum within a blurp in general displayed a great deal of fine structure (Fig. 10).

In 100 wppm concentration (Fig. 11) the noise blurps occurred less frequently than in the case of the 0 wppm concentration. The frequency content appeared to be the same, but the frequency spectrum (Fig. 12) shows a smoothing of the fine structure prevalent in the 0 wppm concentration.

2. Narrow Band Analysis. The 3 inch-2 weight sphere was considered in this analysis for 0 wppm concentration (Fig. 13). Since there was no detectable sound for this sphere in the 100 wppm concentration, no comparison can be made. As seen in Fig. 13 most of the energy is concentrated in the frequency band 2-30 kHz, with the strongest components in the band 4-15 kHz. This method of analysis gives exactly the same information as the spectrogram.

3. All Pass and Band Analysis. This method showed that the radiant sound for a given sphere under identical drop conditions was not exactly repeatable. Each sphere, however, had a characteristic signature and, with experience a given signature could be readily identified with a given sphere. This signature was not significantly different for runs in the anechoic and reverberant tanks, thereby giving confidence in the validity of the data collected in the reverberant tank.

For three "noisy" spheres (3.93 inch, 3 inch two weight, and 3 inch no weight), the largest blurp present in the 100 wppm concentration had a magnitude at least 50 percent less than the largest observed in the 0 wppm concentration. In addition, the total number of blurps observed were substantially reduced in the 100 wppm solution.

The band analysis of a given sphere showed that a blurp contained all frequencies up to 98 kHz.

4. Integrated Analysis. The following data represent the integrated value of the radiant sound above the background level, averaged over at least five drops per sphere. This relative value is proportional to energy and it represents the value immediately before the sphere strikes bottom.

Sphere	0 wppm	100 wppm
3 inch - 1 wt.	.21	.06
3 inch - 2 wt.	.18	.00
3.93 inch	.18	.09
2 inch	.08	.00
3 inch - no wt.	.04	.02
1 inch	.02	.00
6 inch	.00	.00

The background level averaged over eight different readings taken on three different days showed an average DC value of .86 for 0 wppm concentration. For the 100 wppm concentration this average background level showed an average DC value of .27 based on eleven readings on two different days.

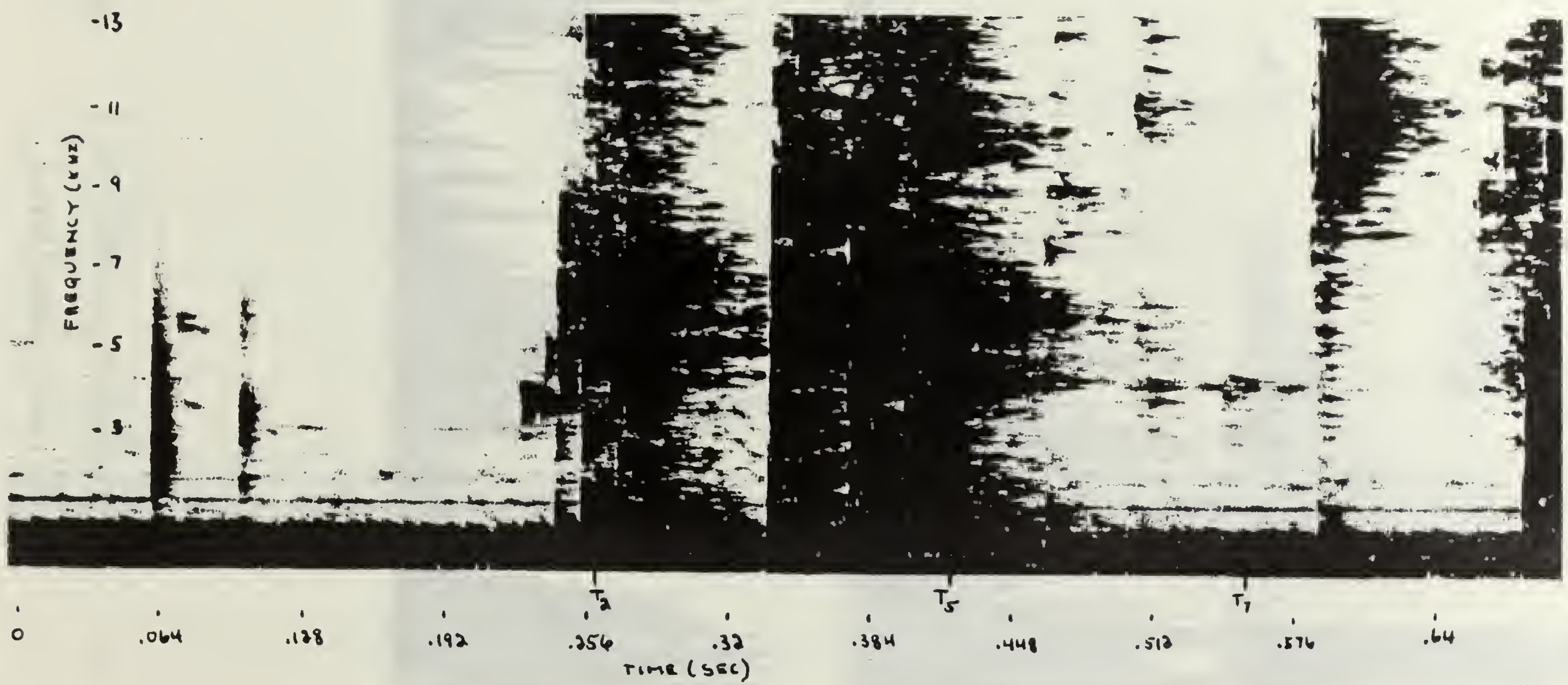


Figure 9. Time history of the noise produced by 3.93 inch sphere falling in 0 wppm concentration

Figure 10. Spectrum of noise produced by 3.93 inch sphere falling in 0 wppm concentration at instant of noise bursts

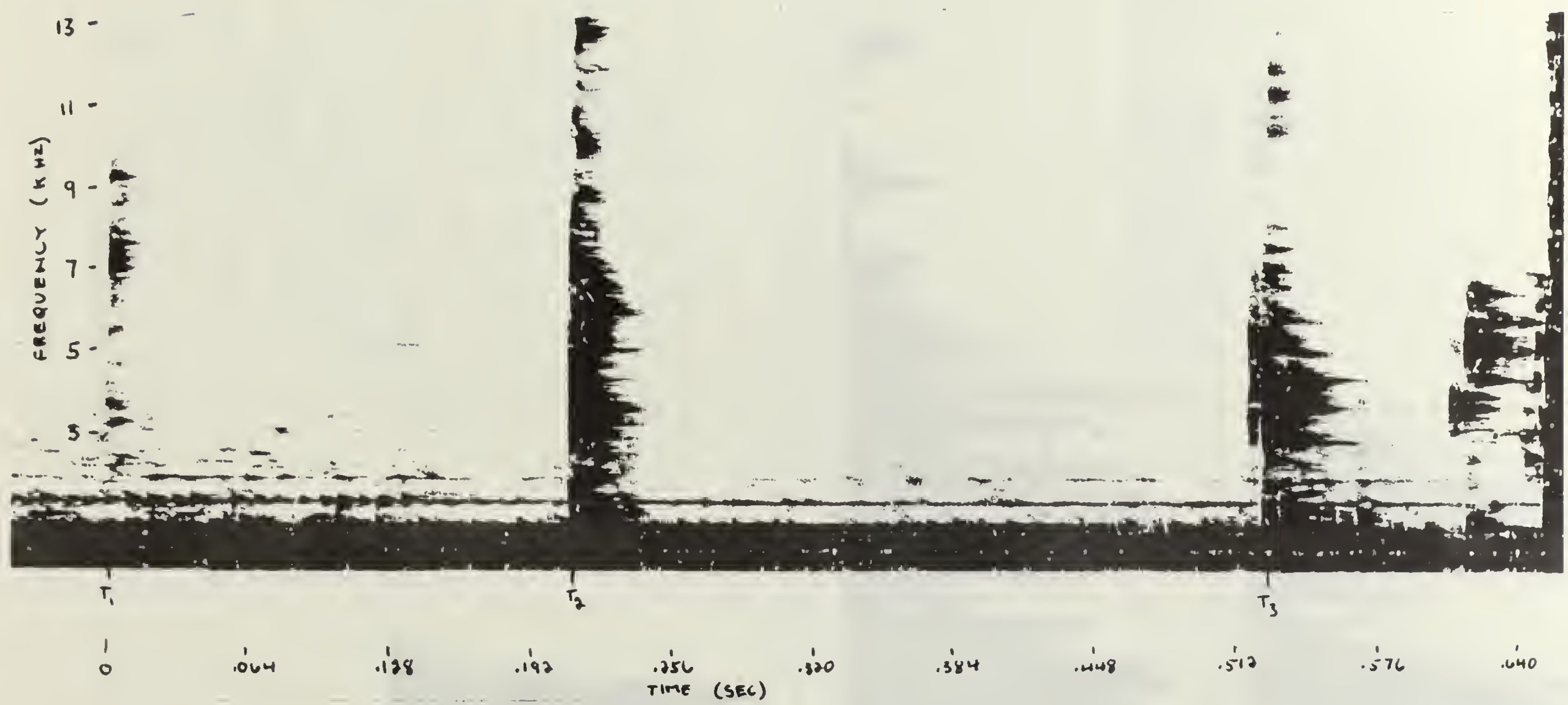


Figure 11. Time history of the noise produced by 3.93 inch sphere falling in 100 wppm concentration

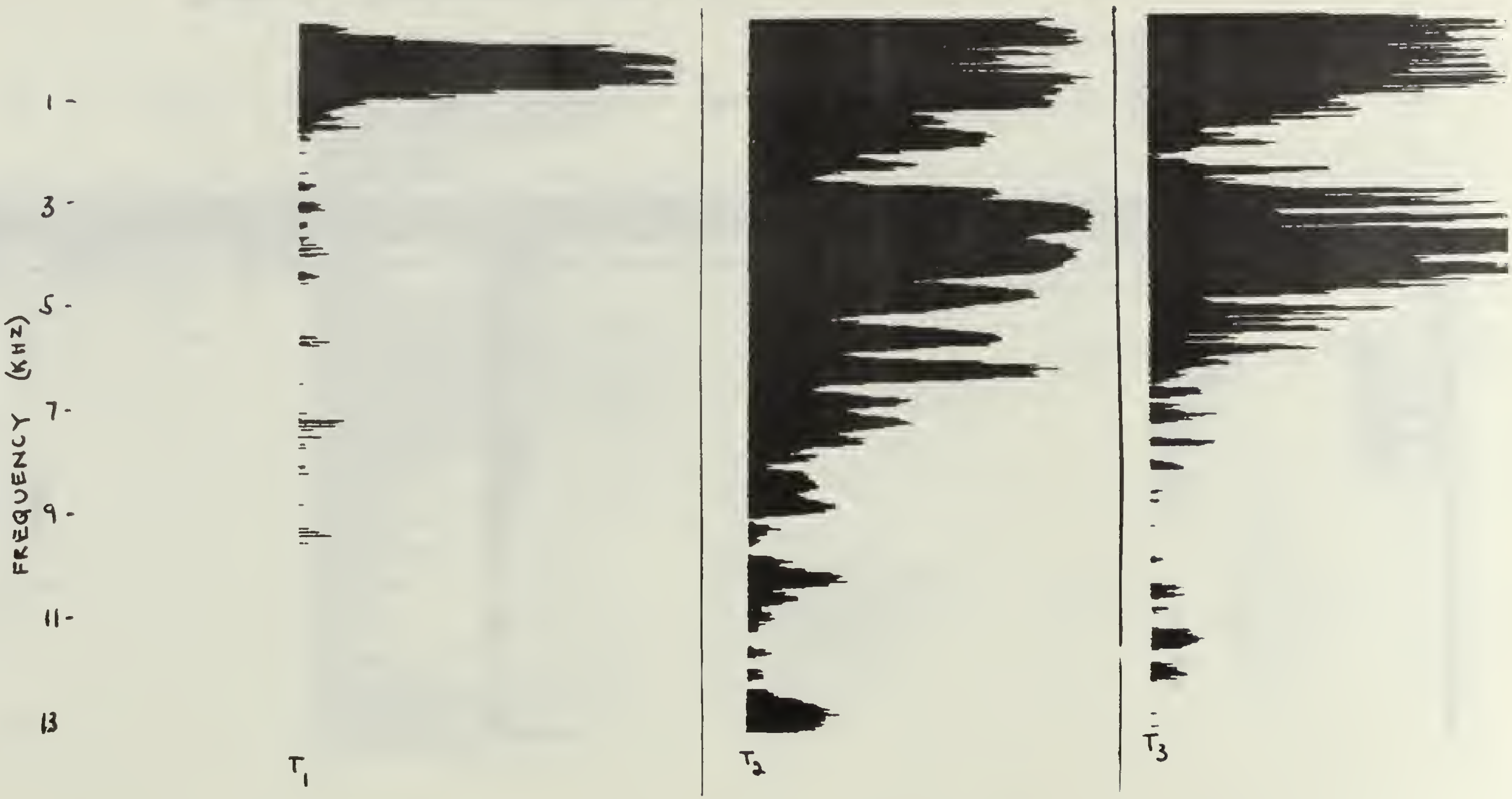
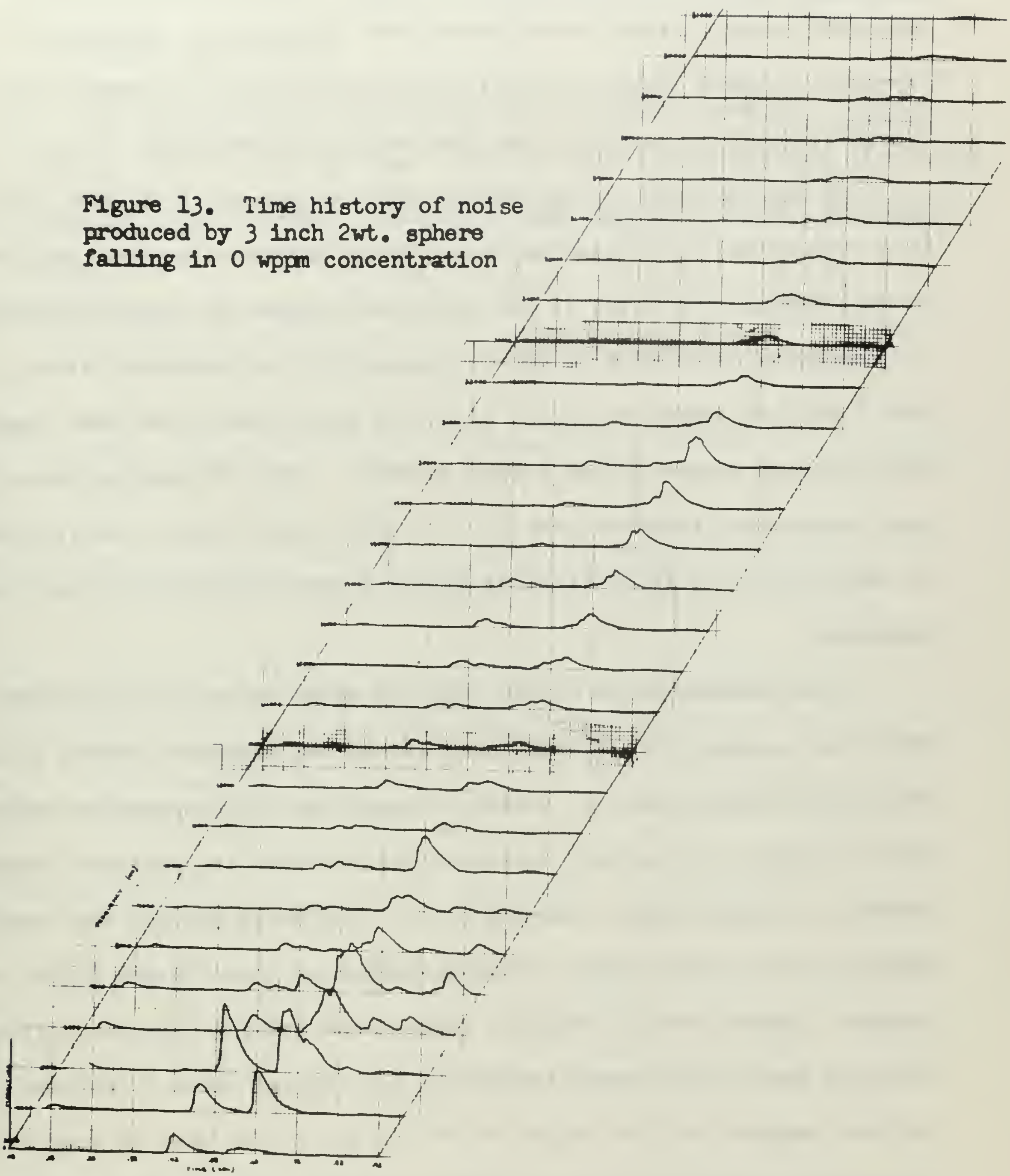


Figure 12. Spectrum of noise produced by 3.93 inch sphere falling in 100 wppm concentration at instant of noise bursts

Figure 13. Time history of noise produced by 3 inch 2wt. sphere falling in 0 wppm concentration



8. Conclusions

In the 0 wppm solution, the major contributors to the radiant sound were distinctive noise bursts or blurps whose rate of occurrence increased with increasing Reynolds number. At or above the critical Reynolds number, these noise bursts were consistently observed. For Reynolds numbers less than critical the noise bursts occurred infrequently,and when they did occur they were of a low level.

At the 100 wppm concentration, only the sphere (3.93 inch) with the highest speed radiated any significant amount of sound. For the other spheres, the level of the noise was reduced to below background (a reduction of as much as 15 dB), except for an infrequent blurp. The 3.93 inch sphere displayed blurps of much lower level than observed for the same sphere in the 0 wppm solution. The 100 wppm solution did not change the frequency content of a given noise burst, but it tended to smooth out the fine structure that was characteristic of the 0 wppm solution.

It is reasonable to assume that the noise bursts are associated with some property of the wake that exists for Reynolds numbers at or above the critical value. Evidence supporting this assumption comes from the fact that polymer solutions tend to move the critical Reynolds number to higher values, Chenard [14]. This would explain why spheres above but near the critical Reynolds number in water become silent in Polyox. Spheres with a Reynolds number much greater than the critical value in water still make significant but reduced noise in Polyox. Further support for the origin of the bursts in the wake is supplied by Whinny's observation of "crackling sounds", picked up by a surface probe placed at the point where the separation associated with the critical Reynolds number occurs.

Unfortunately, no visual observations of the wake have indicated any mechanism that might be associated with these noise bursts. Evidence of the association between the noise bursts and some phenomenon in the wake might be obtained by correlating dye streak photography with sound measurement.

No matter what the origin of the bursts produced by a freely falling blunt body, the same dilute polymer solutions that cause drag reduction also virtually eliminate this prominent source of radiant noise.

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13. ABSTRACT

Sound radiated by spheres freely falling in aqueous solutions of poly(ethylene oxide) WSR-301 at concentrations 0 and 100 wppm was investigated. In solution of 0 wppm concentration, only those spheres with calculated Reynolds numbers (based on the terminal speed) at or above the critical value radiated sufficient energy to be detected above the background. This sound consisted of frequent, distinct noise bursts. In the 100 wppm solution, all spheres with Reynolds numbers near the critical value displayed an increase in speed and a reduction of radiant sound to below background. The one sphere definitely in the supercritical region did not significantly change in speed, and the radiant sound was not reduced as much as for the other spheres. These observations are consistent with the assumption that the noise bursts are produced in the wake associated with laminar separation, and with the previous observation that polymer addition shifts the critical Reynolds number to higher values.

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Noise Reduction						
Poly(ethylene oxide)						
Blunt bodies						
Critical Reynolds number						